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THE DYNAMICS OF TURIN METROPOLITAN AREA: A MODEL FOR THE ANALYSIS OF THE PROCESSES AND FOR THE POLICY EVALUATION

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ABSTRACT

A comprehensive model which simulates both the spatial dynamics of an urban system and the impact of urban policies is being applied to the Turin metropolitan area. The socio-economic aspects of the model are based on the causal structure of the Lowry model and the spatial aspects on Wilson's entropy maximizing method; the mathematical formalization was inspired by the Forrester model.
This paper presents the structure and working of the general model focussing in particular on the location residential submodel.
Problems and results of the model calibration are discussed and the outcome of the simulation of certain socio-economic scenarios are illustrated.
The main potentialities of the model as it stands are described and possible future developments are suggested.

1. INTRODUCTION

This paper deals with the application of a comprehensive model to the Turin metropolitan area.
The model derives from past modeling experience at IRES (Bertuglia and Rabino 1975, IRES 1976) and was originally conceived in 1980 (Bertuglia et al. 1980) with the specific aim of simulating the socio-economic and spatial dynamics of an urban system and the impact of urban policies.

This paper is divided into three parts. In the first we briefly describe the socio-economic and spatial characteristics of the study area as well as the processes of growth which have occurred in the Turin urban system in the past thirty years.
Then in the second part we present the theoretical structure and the working of the simulation model (running and interrelationships of the submodels) and illustrate the methodological and operational aspects of the model calibration. We focus, in particular, on the location residential submodel which besides being the heart of the overall model, is the submodel which created the most difficult but most stimulating calibration problems.
In the last part we illustrate the main results of the model calibration as well as the outcome of some simulation experiments for three different socio-economic scenarios, which provide the necessary background for policy analysis.
In addition, in the concluding comments the main potentialities of the model are discussed, and directions for possible future developments of the model are suggested.

2. CHARACTERISTICS AND PROCESSES OF GROWTH OF THE STUDY AREA

The study area is in the Piedmont Region and covers a total area of 4,924 square kilometres. It is centred on Turin but includes part of the Alpine Chain, a section of the Po Valley and adjacent hill areas (50% of the study area is mountainous, 20% hills and 30% plain). The most important industries and population are concentrated in the lowland part (city of Turin and surrounding areas), see Figure 1.

The study area has been subdivided into 99 zones; 53 of these make up the city of Turin itself and the other zones consist of groupings of the communes outside the city. (A commune is an administrative area and is also a basic unit of census information).

The resulting pattern of zones is increasingly close-knit towards the centre of the study area, reflecting the socio-economic weight of the city itself, see Figure 2 and Figure 3. (In Figure 2 we also show the division of the study area into rings).

The present structure of the Turin urban system is the result of a process of growth which was remarkable for its speed and its dependence on one strongly dominant economic sector.

The process of socio-economic and spatial growth which took place in the Turin urban system from 1950 to 1980 can be analysed in terms of the following phases of development (Bertuglia et al. 1983b):

a. first phase open system (1951-1960). We see the take-off of the system and together with this a rapid socio-economic development of the city with the consequent triggering of the process of spatial growth of the system. In this period the economic growth (which mainly occurs in manufacturing industry), generates a strong immigration dynamic affecting in particular the city of Turin;
b. second phase: transient system (1961-1970). In this period the socio-economic development although less rapid than previously, spreads outwards leading to a fast and chaotic process of urbanisation of the areas surrounding the city and along the main communication routes (oil - spot effect);
c. third phase: closed system (1971-1980). The socio-economic development slows down: the immigration dynamic disappears and the economic growth weakens, growth occurring prevalently in the service sector. In this phase spatial expansion continues but more slowly, affecting the outer areas of the city and the spaces still vacant in the already urbanised areas to a

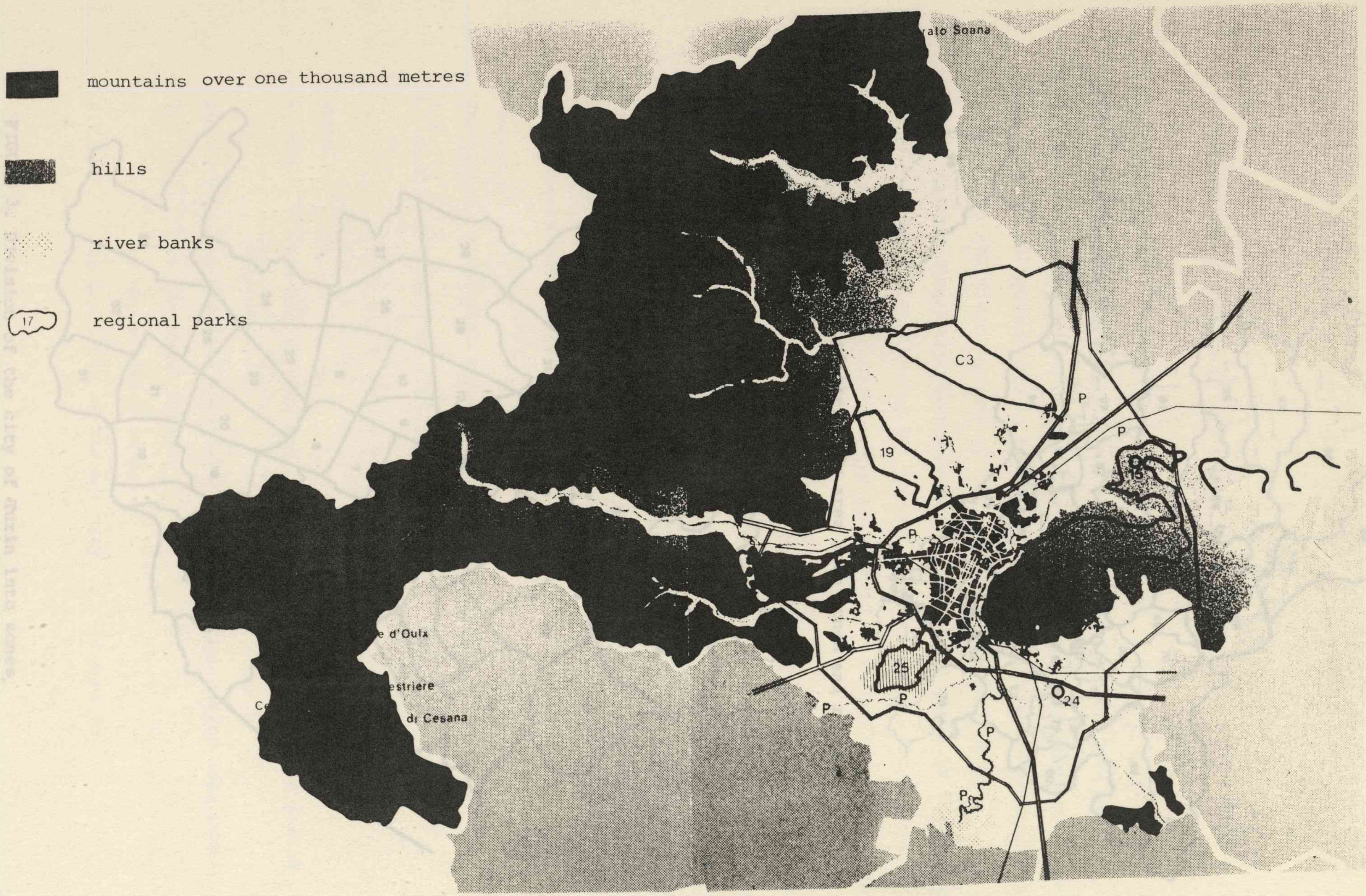


FIGURE 1. The study area: physical characteristics.

FIGURE 2. Division of the study area into zones and rings.

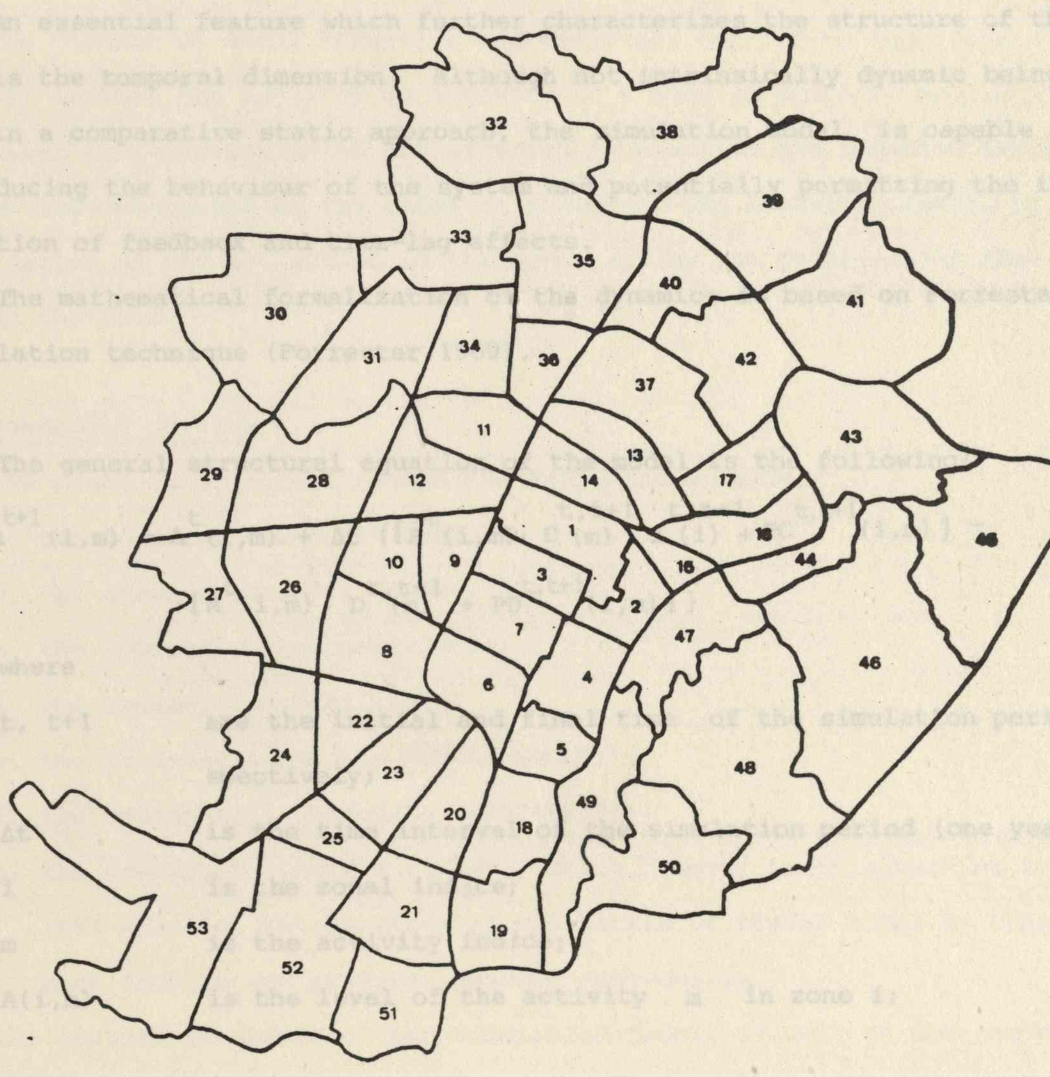


FIGURE 3. Division of the city of Turin into zones.

greater extent than before.

3. THEORETICAL STRUCTURE OF THE MODEL

Introduction

Two main components underlie the theoretical structure of the model:

a) the activity component which takes account of the socio-economic relationships in the system. One of the socio-economic relationship considered is based on the causal scheme of the Lowry model (Lowry 1964);

b) the spatial component which models the effects of space in the system (capacity constraint of zones and spatial interaction relationships). The spatial interaction relationship is modeled on Wilson's entropy maximizing method (Wilson 1970).

An essential feature which further characterizes the structure of the model is the temporal dimension. Although not intrinsically dynamic being rooted in a comparative static approach, the simulation model is capable of reproducing the behaviour of the system and potentially permitting the incorporation of feedback and time-lag effects.

The mathematical formalization of the dynamics is based on Forrester's simulation technique (Forrester 1969).

The general structural equation of the model is the following:

$$A^{t+1}(i,m) = A^{t}(i,m) + \Delta t \{[A^{t}(i,m) \cdot C^{t,t+1}(m) \cdot Z^{t,t+1}(i) + PC^{t,t+1}(i,m)] - [A^{t}(i,m) \cdot D^{t,t+1}(m) + PD^{t,t+1}(i,m)]\} \quad (1)$$

where

t, t+1 are the initial and final time of the simulation period respectively;

Δt is the time interval of the simulation period (one year);

i is the zonal indice;

m is the activity indice;

A(i,m) is the level of the activity m in zone i;

C(m), D(m) are the positive and negative rate of change of the activity m respectively;

Z(i) is the attraction factor for the activity m in zone i, which is given by:

$$Z^{t,t+1}(i) = \sum_j L^{t,t+1}(i) \cdot e^{-\theta\sum_v T(v,i,j)\cdot RM(v)} \Big/ \sum_i\sum_j L^{t,t+1}(i)\cdot e^{-\theta\sum_v T(v,i,j)\cdot RM(v)} \qquad (2)$$

where

L(i) is the land availability in zone i for the activity m;

θ is the impedance parameter of distance;

T(v,i,j) is the travel time from zone i to zone j by transportation mode v;

RM(v) is the modal split coefficient by transportation mode v;

PC(i,m), PD(i,m) are the construction and demolition programmes of activity m in zone i, respectively.

The concept of model structure and behaviour implied by equations (1) and (2) is that the level of an activity in a zone is progressively altered through time by changes which are affected by positive and negative feedbacks. These are determined by the rates of change of the activity itself, by the variation of the attraction of the zone, and by the policies for that activity in the zone.

Submodels working

The model is organised around the following submodels:

a. the industry submodel (IND);
b. the service submodel (TERZ);
c. the population submodel (POP);
d. the housing submodel (AB);
e. the land-use submodels (SUOLI+SUOLFI);
f. the residential submodels (RESI+RESFI);
g. the transport submodel (TRASP) which, however, in this version is not a real submodel but consists of the matrix of travel times by transportation mode (public and private) assumed exogenously.

The general framework of the simulation model, as well as the sequence of execution of the submodels and their interrelationships are shown in Figure 4.

Before describing the main operations of the submodels it should be pointed out that since the original formulation in 1980 (Bertuglia et al. 1980), the overall model has undergone improvements and modifications which were motivated by (Bertuglia et al. 1982a, 1982b): a) a deep analysis of the past growth processes of the system which yielded a development of the land-use submodel. In particular a refinement in modeling land availability for the different activities in zones and the effects of the resulting zone carrying capacity on the activity levels; b) a need for a more manageable model. As the original model was far more disaggregated, the dimensions of the non spatial indices of the model have been reduced.

The model indices are: i residential zone (i=1,99), j workylace zone (j=1,99), s housing type (s=1,6), r base sector (agricolture, industries, high-level services) (r=1,4), l service sector (low-level service) (l=1), f family-type for families with employed family-head (f=1,8), g family-type for families with unemployed family-head (g=1,4), v transportation mode (v=1,2).

The main operations performed by each submodel are summarized in Table 1.

The mathematical formalization of the submodel operations are variants of the general Equation (1) except for the land-use submodel (SUOLI) which is based on Equation (2), and for the residential location submodel (RESFI) which is more complex, and will be dealt with later on. In addition, the RESI and SUOLFI submodels perform mainly accounting operations and the POP submodel is a non spatial variant of Equation (1). For sake of brevity, we do not restate the equations of the overall model. The reader is referred to Bertuglia et al. (1982a).

We will now briefly focus on the analytical structure of the residential location submodel which constitutes the heart of the simulation model. To simplify the notation we omit the indices. Let us define.

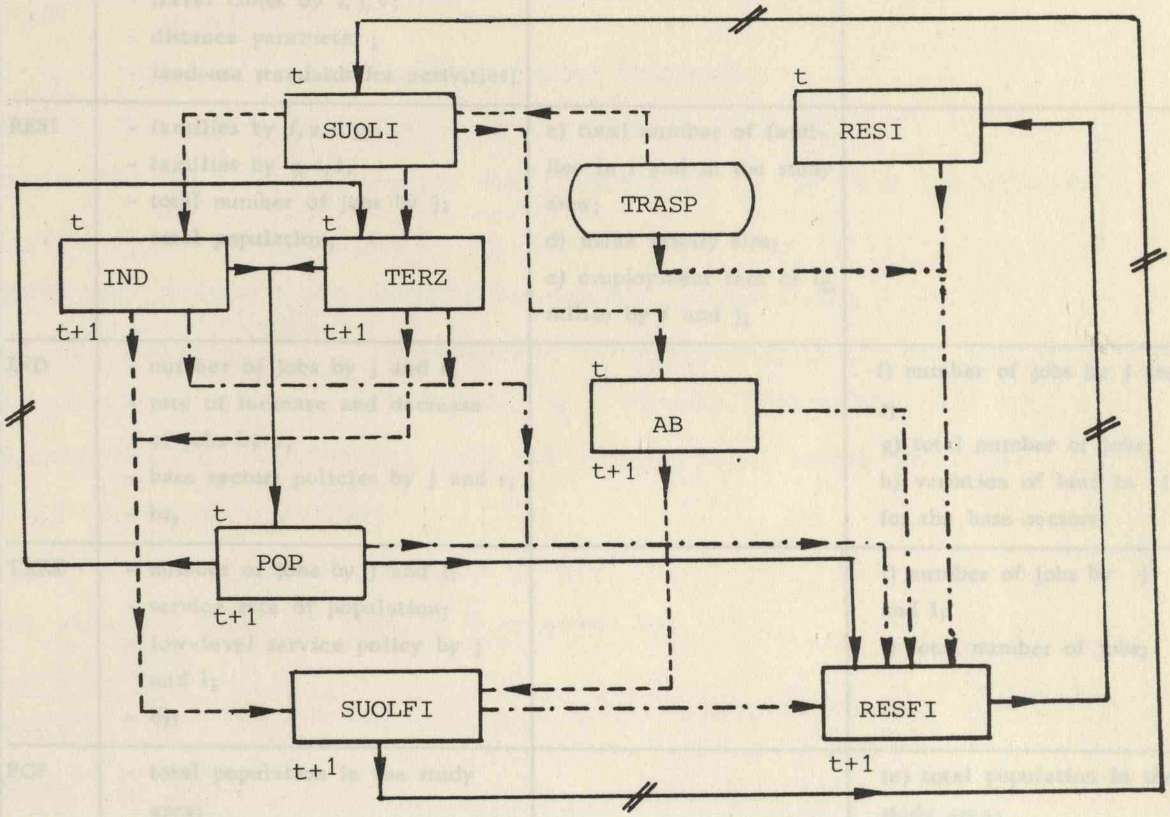


FIGURE 4. Sequence of execution and interrelationships of the submodels.

t   beginning of a simulation interval (1 year)

t + 1   end of a simulation interval

socio-economic interrelationships

spatial interrelationships

residential-location interrelationships

main feedback interrelationships

TABLE 1. Main operations performed by the submodels.

Sub-models	input time t	output time t	output time t + 1
SUOLI	- land occupied and in project for each activity in i, j; - land-use policies (new destinations, reallocations) in i, j; - travel times by i, j, v; - distance parameter ; - land-use standards for activities;	a) land availability for each activity in i, j; b) attractivity factors for each activity in i, j;	
RESI	- families by f, s, i, j; - families by g, s, i; - total number of jobs by j; - total population;	c) total number of families in i and in the study area; d) mean family size; e) employment rate of families by f and j;	
IND	- number of jobs by j and r; - rate of increase and decrease of jobs by r; - base sectors policies by j and r; - b);		f) number of jobs by j and r; g) total number of jobs; h) variation of land in j for the base sectors;
TERZ	- number of jobs by j and l; - service rate of population; - low-level service policy by j and l; - c);		i) number of jobs by j and l; l) total number of jobs;
POP	- total population in the study area; - birth, death, migration and employment rates of population; - g), l);		m) total population in the study area;
AB	- number of houses by i and s; - building and demolition rates by s; - housing policies by i and s; - b);		n) number of houses by i and s; o) variation of land in i for houses;
SUOLFI	- a), h), o);		p) land occupied by each activity in i, j;
RESFI	- families by g, s, i; - c), d), e), f), i), m), n); - travel times by i, j, v; - utility weighting factors; - distance parameter; - utility parameter;		q) families by g, s, i; r) families by f, j; s) utility functions by f, i, s; t) families by f, i, s, j (determined through an origin constrained spatial interaction model).

O	total number of jobs (calculated in the industry and service submodels);
KO	inverse of the mean rate of employment of households;
Q = O/KO	total number of households (with employed family heads);
TPROB	probability of utilization of transport mode;
T	travel costs (transportation submodel);
AB	housing (calculated in the housing submodel);
SLAO	land in residential use (calculated in the land use submodel);
K, H, N	weighting factors;
TETA, CSI	distance and utility parameters, respectively;

$A = \Sigma Q \cdot TPROB \cdot e^{-TETA \cdot T}$ residential accessibility. (3)

The utility (real utility) derived by a household from the choice of a residential bundle (residential zone and housing type) takes the form:

$$U = K \cdot \overline{A} + H.\overline{AB} + N \cdot \overline{SLAO} \tag{4}$$

(where $\overline{x}$ is the normalised value of x).

The expected value of utility $\overline{U}$ is given by:

$$\overline{U} = \Sigma U \Sigma \frac{DPOTO}{Q} \tag{5}$$

where

$$DPOTO = Q \cdot \frac{WT}{\Sigma WT} \tag{6}$$

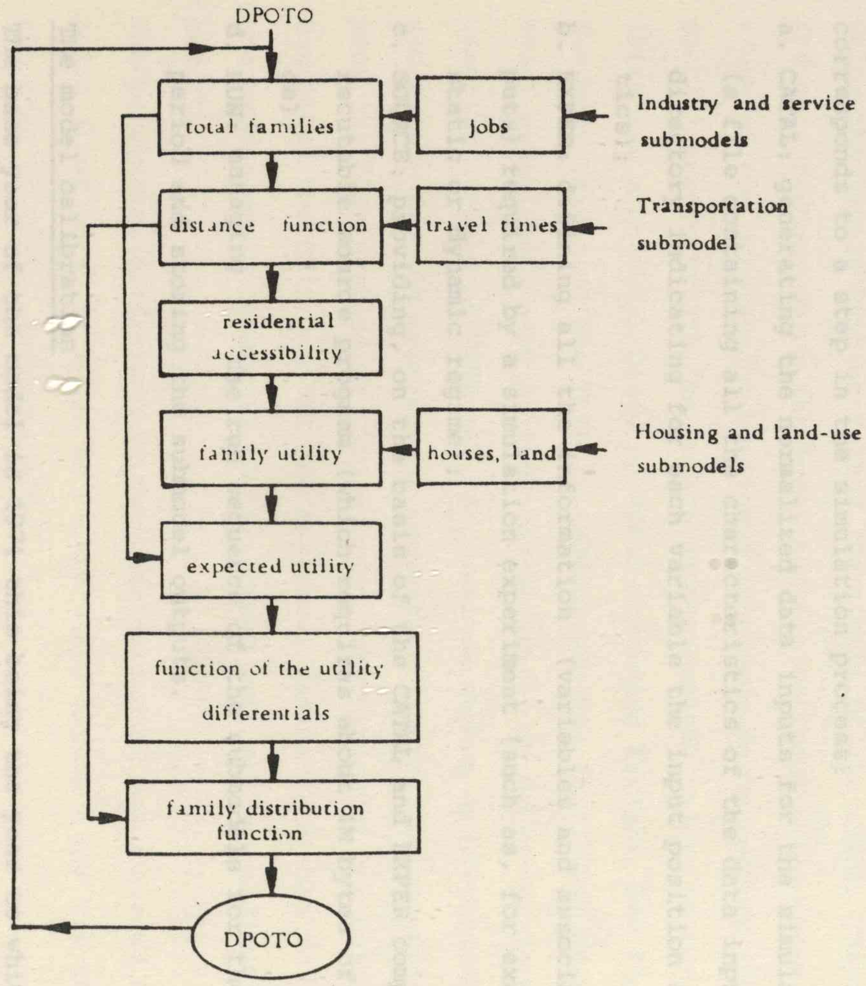
and

$$WT = \Sigma TPROB \cdot e^{-TETA \cdot T} \cdot \Sigma\, e^{-CSI(\overline{U}-U)} . \tag{7}$$

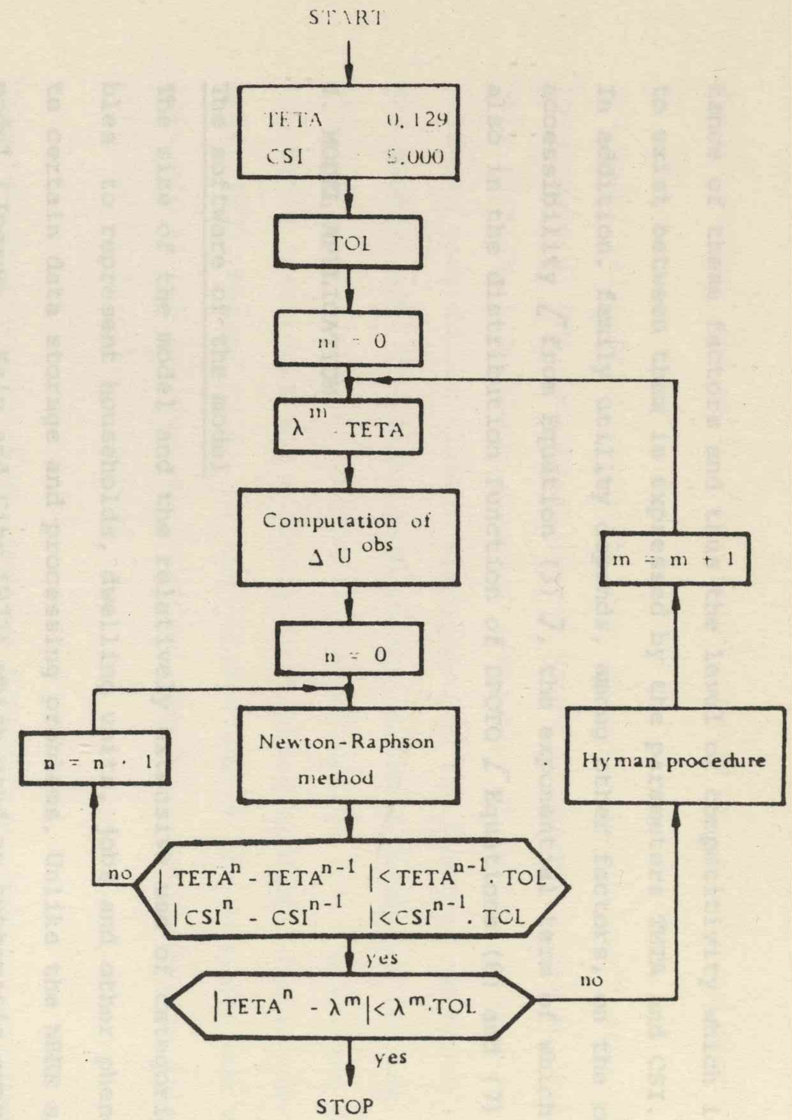
DPOTO is the representative variable of both the residential and workplace location of families (broken down by family type).

Model (3)-(7) is based on the hypothesis that not all the families are likely to find an optimal residential location: some attain a higher utility level than expected, while others remain below it. In this way, the model tries to describe a real market, providing a measure of demand and supply disequilibrium based on the difference between the real and the expected utility of families (Anas 1973). A diagrammatic representation of model (3)-(7) is given in Figure 5a.

It can be seen that the residential distribution of families depends on two main factors: a spatial factor (distance function) and a factor measuring family welfare (function of the utility differentials). The relative impor--



5a. Structure of the submodel.



5b. Diagram of the calibration procedure.

FIGURE 5. Structure and calibration procedure of the residential location submodel.

tance of these factors and thus the level of competitivity which is likely to exist between them is expressed by the parameters TETA and CSI.

In addition, family utility depends, among other factors, on the residential accessibility /̲ from Equation (3) _7, the exponential term of which appears also in the distribution function of DPOTO /̲ Equations (6) and (7) _7.

4. MODEL APPLICATION

The software of the model

The size of the model and the relatively extensive use of categorical variables to represent households, dwelling units, jobs and other phenomena, create certain data storage and processing problems. Unlike the NBER simulation model (Ingram, Kain and Ginn 1972) which used an authomatic overlay technique for the management of large arrays our overall simulation program can be directly dealt with by the operating system (IBM OS/MVS-JES2).

The software structure consists of the following components each of which corresponds to a step in the simulation process:

a. CATAL: generating the normalized data inputs for the simulation program (a file containing all the characteristics of the data input and an input directory indicating for each variable the input position and characteristics);

b. EXPER: defining all the information (variables and associated data inputs) required by a simulation experiment (such as, for example, in a static or dynamic regime);

c. SOURCE: providing, on the basis of the CATAL and EXPER components, the executable source program (which requires about 4M bytes of virtual storage);

d. RUN: managing the run sequence of the submodels for the whole time period and storing the submodel outputs.

The model calibration

The base year of the model is 1971 this being the year to which census infor mation refers. The whole time period covered by calibration goes from 1971 to 1981.

The model calibration required three main operations which were carried out separately. a) The estimation of the rates of change of the activities (industry,service, population, housing submodels) at yearly intervals. This operation was carried out through simulation on the basis of observed trends given exogenously. b) Calibration of the distance parameter for the zonal attraction term (land-use submodel) - see Equation (2) - which was based on the Hyman procedure for a doubly constrained spatial interaction model (see Batty 1976, Baxter 1976). c) The calibration of the distance and utility parameters in the residential location submodel - see Equations (3)-(7) - which will now be friefly presented.

Calibrating the residential location submodel: methodology and results

The methodology for this submodel calibration was based on the maximum likelihood principle according to which two equations of maximum likelihood for the distance (TETA) and utility (CSI) parameters, where derived and resolved using the Newton-Raphson method (Bertuglia et al. 1982b, 1983b).

The main feature which characterized the calibration procedure was that because of the previously mentioned interdependence between utility and residential accessibility the Newton-Raphson scheme had to be nested in an outer iterative structure, based on Hyman converging formula, see Figure 5b.

The best values of the TETA (0.103606) and CSI (5.779334) were found after several experiments each of them characterized by different initial definitions (starting values of TETA and CSI, maximum number of iterations for the Hyman and Newton-Raphson procedures, convergence limit). At the end of each experiment the final values of TETA and CSI, the values of the maximum likelihood equations for TETA and CSI and a general indicator of the deviation between the predicted and observed DPOTO (summed over all the indices) were calculated.

The percentage difference between the predicted and observed DPOTO (for the total flows in i) is shown in Figure 6 and Figure 7 for the study area and the city of Turin, respectively.

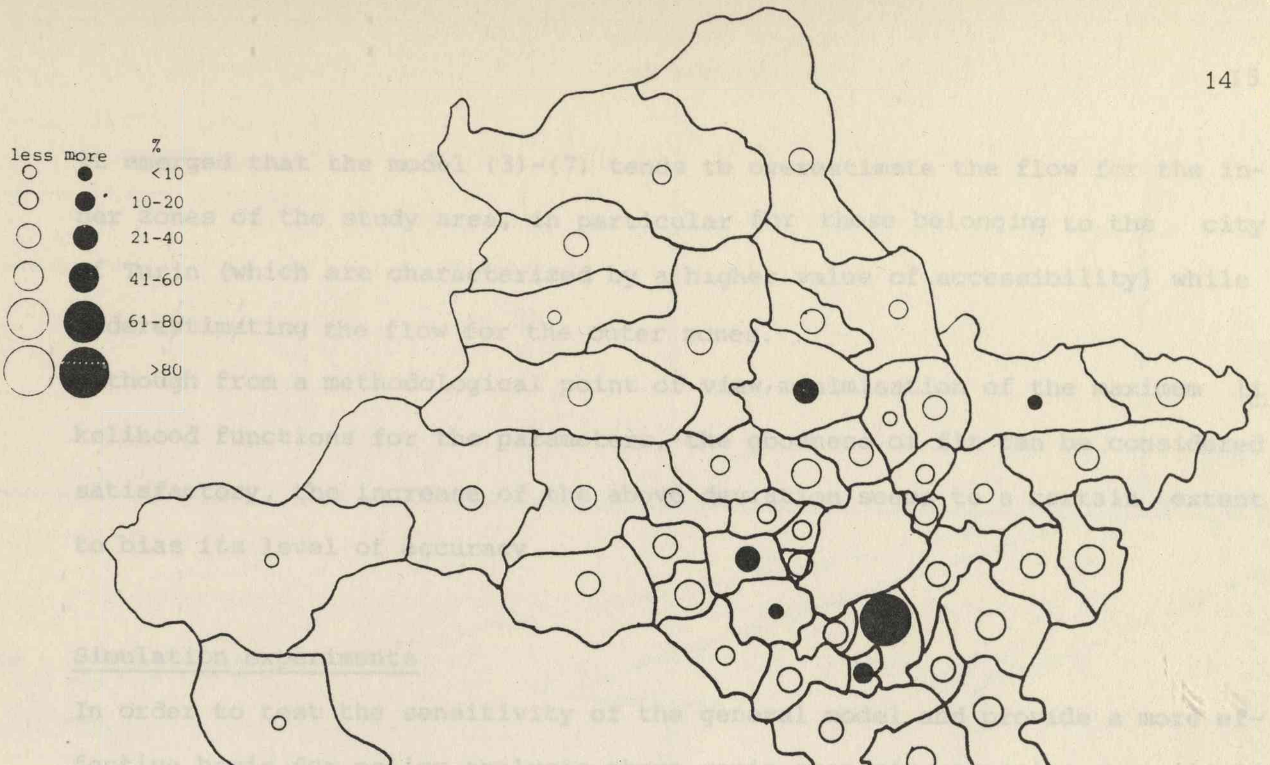


FIGURE 6. Percentage difference between the predicted and observed DPOTO for the zones outside the city of Turin.

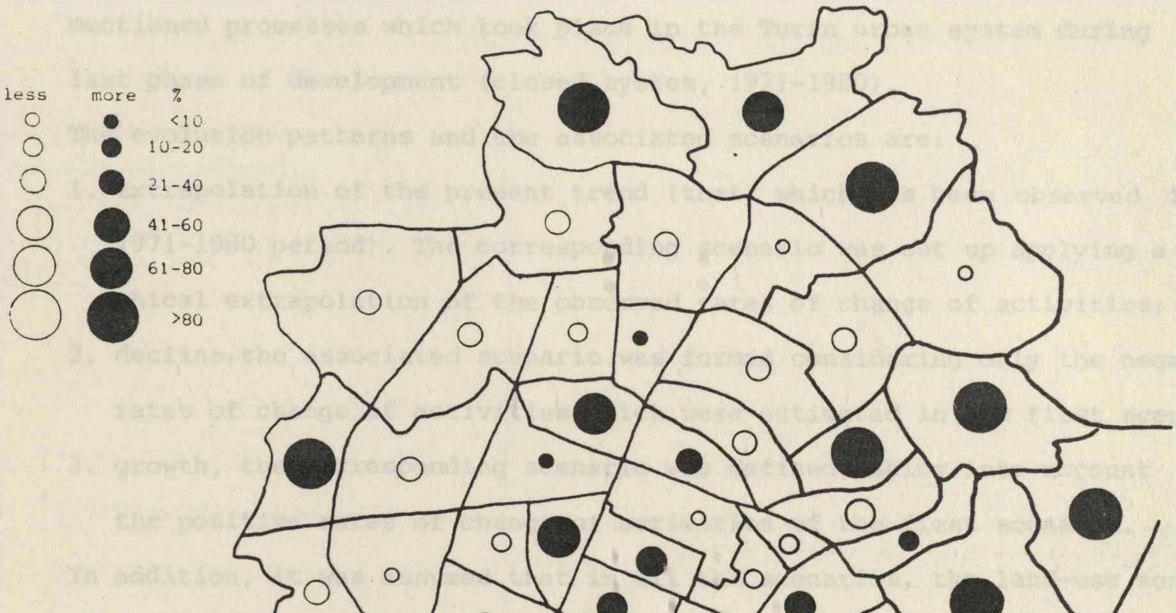


FIGURE 7. Percentage difference between the predicted and observed DPOTO for the zones in the city of Turin.

It emerged that the model (3)-(7) tends to overestimate the flow for the inner zones of the study area, in particular for those belonging to the city of Turin (which are characterized by a higher value of accessibility) while underestimating the flow for the outer zones.

Although from a methodological point of view, minimisation of the maximum likelihood functions for the parameters, the goodness of fit can be considered satisfactory, the increase of the above deviation seems to a certain extent to bias its level of accuracy.

Simulation experiments

In order to test the sensitivity of the general model and provide a more effective basis for policy analysis three socio-economic scenarios were simulated. Each of these represents a different hypothetical pattern of evolution of the system for the period 1981-1999.

To some extent these patterns were derived from the analysis of the previously mentioned processes which took place in the Turin urban system during its last phase of development (closed system, 1971-1980).

The evolution patterns and the associated scenarios are:

1. extrapolation of the present trend (that, which has been observed in the 1971-1980 period). The corresponding scenario was set up applying a graphical extrapolation of the observed rates of change of activities;
2. decline, the associated scenario was formed considering only the negative rates of change of activities which were estimated in the first scenario;
3. growth, the corresponding scenario was defined taking into account only the positive rates of change of activities of the first scenario.

In addition, it was assumed that in all the scenarios, the land-use zoning, travel times, land-use standards of activities and distance parameter remained unchanged.

The dynamics of population and employment which resulted from the simulation of the three scenarios are shown in Figures 8 and 9. These illustrate the path of evolution of the system from 1971 to 1999 for each five-year periods in the different scenarios.

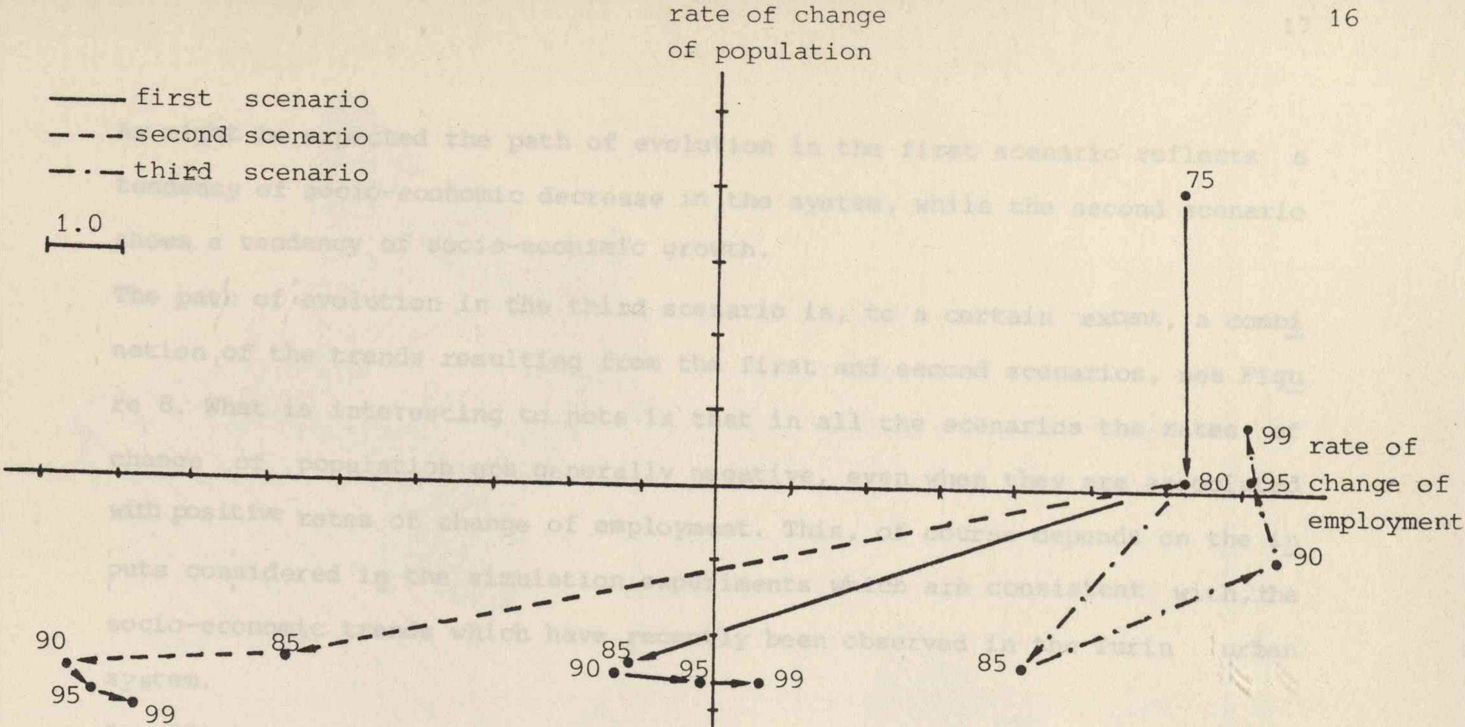


FIGURE 8. Dinamics 1971-1999 of population and employment to five-year periods for the three scenarios (a).

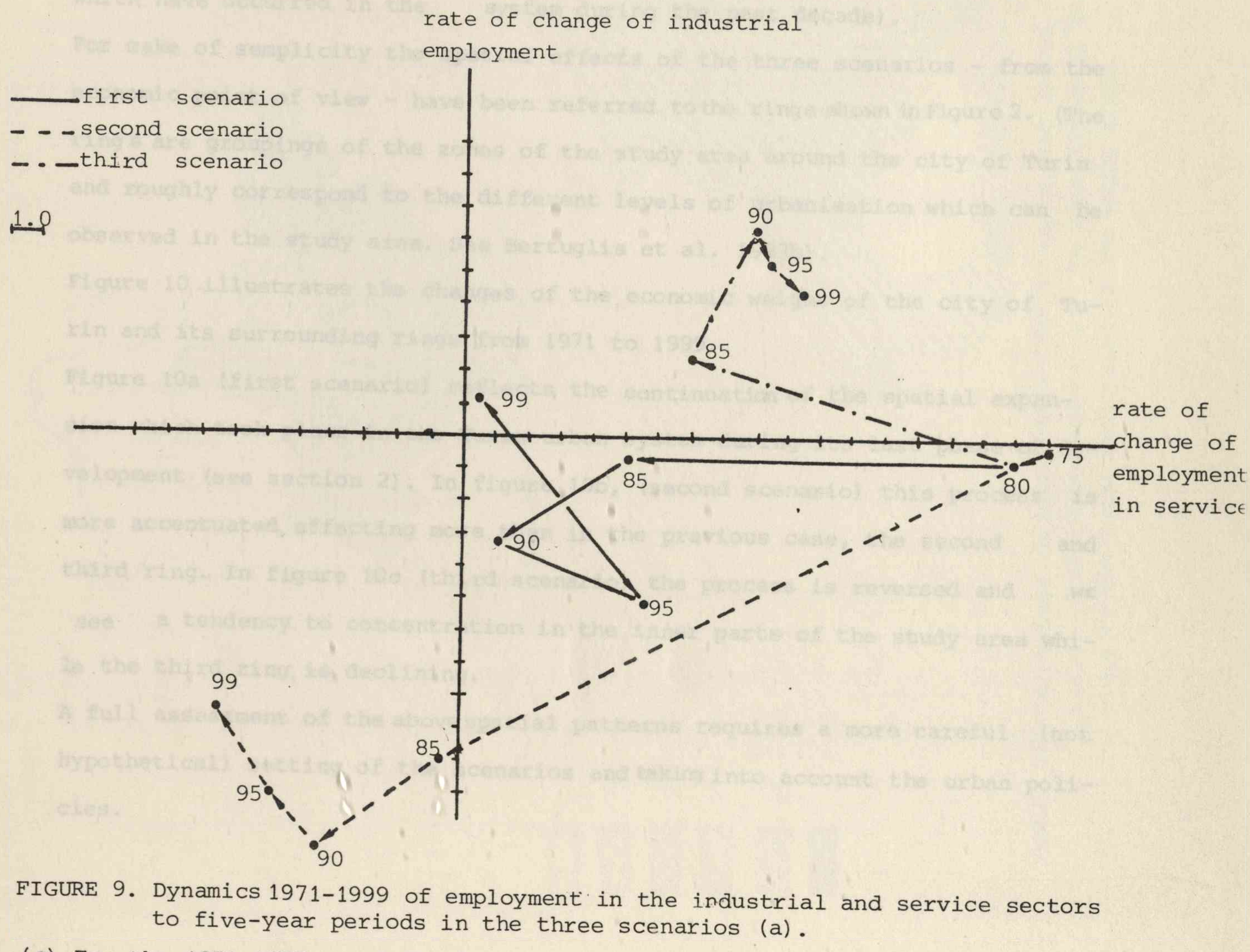


FIGURE 9. Dynamics 1971-1999 of employment in the industrial and service sectors to five-year periods in the three scenarios (a).

(a) For the 1971-1980 period, the rates are the same in three scenarios.

As might be expected the path of evolution in the first scenario reflects a tendency of socio-economic decrease in the system, while the second scenario shows a tendency of socio-econimic growth.

The path of evolution in the third scenario is, to a certain extent, a combination of the trends resulting from the first and second scenarios, see Figure 8. What is interesting to note is that in all the scenarios the rates of change of population are generally negative, even when they are associated with positive rates of change of employment. This, of course depends on the inputs considered in the simulation experiments which are consistent with, the socio-economic trends which have recently been observed in the Turin urban system.

In addition, as shown in Figure 9, in all the scenarios the rates of change in services sectors tend to be higher (when positive) than those in industry, thus indicating a progressively stronger dependence of the economic system on service employment (this is also reflected in the observed trends which have occurred in the system during the past decade).

For sake of semplicity the spatial effects of the three scenarios - from the economic point of view - have been referred to the rings shown in Figure 2. (The rings are groupings of the zones of the study area around the city of Turin and roughly correspond to the different levels of urbanisation which can be observed in the study area. See Bertuglia et al. 1983b).

Figure 10 illustrates the changes of the economic weight of the city of Turin and its surrounding rings from 1971 to 1999.

Figure 10a (first scenario) reflects the continuation of the spatial expansion which took place in the Turin urban system during its last phase of development (see section 2). In figure 10b, (second scenario) this process is more accentuated affecting more than in the previous case, the second and third ring. In figure 10c (third scenario) the process is reversed and we see a tendency to concentration in the inner parts of the study area while the third ring is declining.

A full assessment of the above spatial patterns requires a more careful (not hypothetical) setting of the scenarios and taking into account the urban policies.

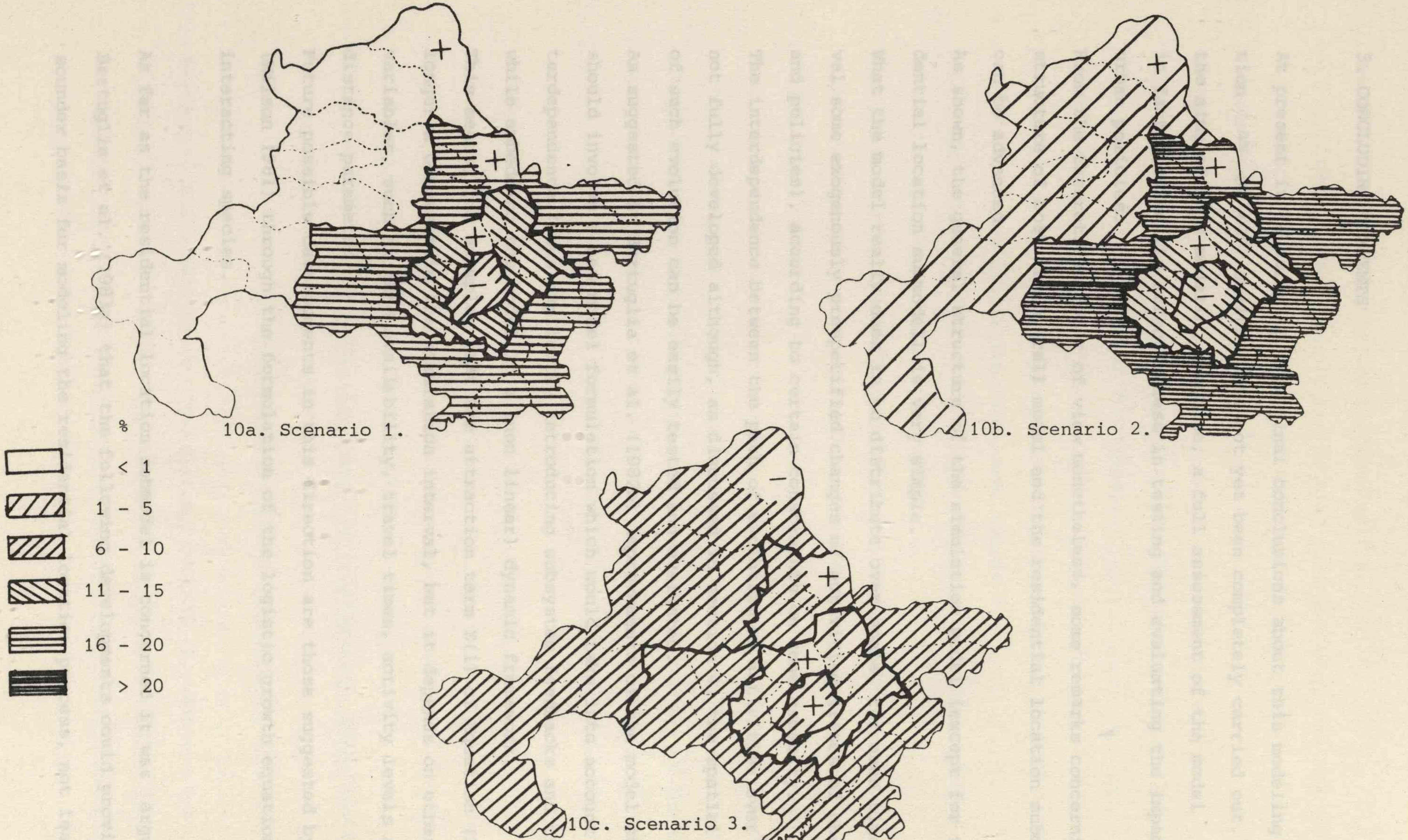


FIGURE 10. Percentage variation 1971-1999 of employment in the city of Turin and the three rings resulting from the simulation of the three scenarios. (The calculation is based on the percentage values of jobs in the city and the rings of the total employment in the study area).

5. CONCLUDING COMMENTS

At present it is early to draw final conclusions about this modeling application as policy analysis has not yet been completely carried out. Given the aims of this modeling exercise, a full assessment of the model should in fact involve its effectiveness in testing and evaluating the impact of the urban policies.

From the theoretical point of view nonetheless, some remarks concerning the structure of both the overall model and the residential location submodel can be advanced.

As shown, the general structure of the simulation model (except for the residential location submodel) is very simple.

What the model really does is to distribute over space, for each time interval some exogenously prespecified changes of activities (rates of changes and policies), according to certain constraints on zone capacity.

The interdependence between the path of evolution of activities over space is not fully developed although, as discussed in section 4, the spatial effects of such evolution can be easily tested and evaluated.

As suggested in Bertuglia et al. (1982b) improvements of the model structure should involve a new model formulation which would take into account this interdependence (thus explicitly introducing subsystem feedbacks and time-lags), while embedding the model in a (non linear) dynamic framework.

This means, for example, that the attraction term Z(i) of Equation (2) is no longer a constant in the simulation interval, but it depends on other system variables, such as land availability, travel times, activity levels and the distance parameter.

Future possible developments in this direction are those suggested by Wilson (Wilson 1981) through the formulation of the logistic growth equations for interacting species.

As far as the residential location submodel is concerned it was argued in Bertuglia et al. (1983a) that the following developments could provide a sounder basis for modeling the residential location process, not least in improving the accuracy of the goodness-of-fit.

a. Logarithmic formulation of residential accessibility, see Equation (4), in order to lessen the impedance effect of distance in the utility function (see, Leonardi 1979).

b. Analysis of the structure of the utility differentials ($\bar{U}$-U).

c. Alternative formulations of the utility functions (using for example, logarithmic or Cobb-Douglas functions).

d. Utilisation of a unique Newton-Raphson sequence for the simultaneous computation of TETA and CSI as well as for the updating of TETA in the residential accessibility function, see, Figure 6.

e. Disaggregation of TETA and CSI by family-type as in the original version of the model (Bertuglia et al. 1980).

f. Introduction in the DPOTO distribution function, see equation (7), of corrective factors associated with destinations (residential zone and housing type).

Some investigation of alternatives b. and f., has already been carried out, in which a slightly better fit (a small decrease in the difference between the predicted and observed DPOTO) was obtained. Exploration of the other alternatives of development is needed and is at present being undertaken.

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*2 "Metodologie per la pianificazione dei parchi regionali", *gennaio 1981*

*3 "A Large Scale Model for Turin Metropolitan Area", *maggio 1981*

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